

# Enhancing Microbial Activity with Rotten Rice Flour to Facilitate Heavy Metal Remediation and Bioenergy Generation via Microbial Fuel Cell



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**ABSTRACT:** Microbial fuel cells (MFCs) have emerged as an innovative approach to addressing environmental pollutants while producing renewable energy. The selection of appropriate substrates plays a pivotal role in fostering microorganism growth and enhancing bioremediation. This study explores the incorporation of rotten rice flour (RRF) as a substrate in MFCs, evaluating its impact on microbial metabolism, bioenergy generation, and bioremediation of toxic metals. The MFC process, lasting 37 days, produced a peak voltage output of 200 mV on day 21 demonstrating the potential of RRF as a sustainable and effective substrate for microbial growth and bioenergy generation. The MFC cycle generates final bioremediation efficiencies of 83.78%, 85.44%, 87.10% for  $\text{Al}^{3+}$ ; 85.54 %, 87.54, 88.90 for  $\text{Cu}^{2+}$  and 87.00%, 90.92%, 93.34% for  $\text{Pb}^{2+}$  respectively indicating its potential in ameliorating toxic metal levels. The organic substrate, rotten rice flour was applied to the anodic region daily throughout the experiment. Furthermore, bacteria analysis was investigated on the anode electrode after MFC operation which revealed the presence of *Staphylococcus aureus*, *Escherichia coli*, *Serratia* sp. and *Bacillus* sp. respectively. The findings suggested that rotten rice flour could serve as an effective organic substrate for applications involving MFC. Furthermore, this research sheds light on the existing prospects of MFC technology and proposes insightful recommendations for its future development.

**KEYWORDS:** Bioenergy; Bioremediation; Microbial Fuel Cell; Rotten Rice Flour; Toxic metals; Wastewater Treatment

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## I. INTRODUCTION

The present world increasingly depends on electricity generation to power industries, houses, gadgets, automobiles which must be constantly provided. To meet with the huge demand for energy, an ample production capacity must be installed which will tally with carbon emission standards (Sumaila et al., 2020). In an attempt to find sustainable remedy, humans have invented various processes of energy generation which includes solar, hydel, wind power and biological based alternatives such as biomass, biogas and microbes. Microbial fuel cells (MFCs) employ a remarkable

and viable technology among other renewable sources of interest because of the utilization of organic and inorganic substrate for bioelectricity production (Magaji et al., 2023; Munoz-Cupa et al., 2021; Suleiman, Guerrero-Barajas, et al., 2025). The incorporation of MFC technology in wastewater technology has been found to suppress chemical oxygen demand (COD) and other pollutants making it a reliable choice to conventional treatment methods. COD measures the amount of oxygen required to chemically oxidize organic (and some inorganic) matter in water, in other words, it is a measure of how much oxidizable organic matter is present.

The higher the rate of organic pollution, the more oxidation required and this increases COD value (Yanuka-Golub et al., 2021). The dual nature of MFCs such as wastewater treatment and bioenergy production have mitigates energy challenges making them a better option for sustainable development (Suleiman, Itopa, et al., 2025; Yaqoob, Idris, et al., 2022). The design of MFCs can change with configurations including single and dual-chamber systems, which affect their efficiency and power production. Although MFC has achieved remarkable scientific ground-breaking in recent years, it still suffers some setbacks in terms of commercial purposes. Factors which include the choice of anode materials, the type of microorganisms used, organic substrate and the operational parameters significantly affect the performance of MFCs (Idris et al., 2022; Suleiman, Itopa, et al., 2025).

Several anode materials including the fabrication of advanced anodes have been applied in MFC to enhance electron transportation and improve overall performances (Idris, Noh, et al., 2023). In a similar effort to enhance MFC performance, various substrates have been utilized in different amounts to evaluate the optimal performance in MFC (Alshammari, Aleid, et al., 2025; Ibrahim et al., 2025). The use of the diverse nature of organic substrates to generate bioelectricity through microbial metabolism is highly considerable due to the biocompatibility nature of the substrate and the provision of carbon sources for microbial growth. A number of general substrates used include biomass, fruit waste, and livestock manure with huge composition of organic matter for microbial activity. (Emmanuel et al., 2021; Emmanuel et al., 2024; Idris et al., 2025).

Agro-processing industries typically generate nutrient-dense agricultural by-products. (Kumbhar et al., 2021) In a similar vein, a significant source of waste is agricultural wastewater

that contains numerous carbon-based substances, which consequently impacts the water bodies it enters when discharged without treatment (Yang et al., 2021). Agricultural residues are recognized as a significant source of energy and carbon. The sugars they contain can be extracted through the application of dilute acids or enzymes (Alshammari, Yaqoob, et al., 2025; ElMekawy et al., 2015; Idris, Yaqoob, et al., 2023; Yaakop et al., 2023; Yaqoob, Bakar, et al., 2022; Yaqoob, Ibrahim, Yaakop, et al., 2021). A significant agricultural residue is wheat straw, which has approximately 34–40% cellulose organic carbon content, around 21–26% organic carbon from hemicellulose, and about 11–23% organic carbon derived from lignin. These components can be subjected to hydrolysis, resulting in wheat straw hydrolysate, which can produce a considerable amount of electricity in a MFC (Alshammari & Ahmad, 2025; Rojas Flores et al., 2020). In a similar fashion, unprocessed corn stover is a form of agricultural waste that plays a significant role in electricity generation when utilizing a single-chamber MFC. Although the treatment process was successful, the generated power output was considerably lower than that of an MFC that uses glucose as a substrate (Rajesh & Kumawat, 2023). The preference of substrate remarkably affects the productivity of MFCs, as several organic materials can generate different range of bioenergy depending on their biochemical configuration and the microbial communities involved (Mbugua, 2021). The use of other traditional techniques such as adsorption, membrane separation, photodegradation and phytoremediation to treat wastewater has shown to be inefficient compared to MFCs (Emmanuel et al., 2024; Idris et al., 2021; Idris, Yaqoob, et al., 2023; Sumaila et al., 2020). Table 1 shows the relative performance of agro-waste substrates in MFCs and their COD removal efficiency.

Table 1 Performance of Agro-waste Substrates Utilized in MFCs

Substrate	Reactor Type	Electrode Material	Voltage (V or mV)	Power Density (mW/m <sup>2</sup> )	COD removal (%)	Metal removal / remediation (%)	References
Rotten rice flour	Dual Chamber	Graphite rod	0.32 V	12.7	82%	Cu: 76%, Pb: 69%	Daud et al. (2021)
Banana peel extract	Single Chamber	Carbon cloth	570 mV	38	88%	Pb: 85%, Cu: 78%, Cd: 72%	Verma and Mishra (2023)
Sugarcane bagasse hydrolysate	Single Chamber	Carbon felt	430 mV	14.9	65%	Pb: 71%, Cu: 67%	Christwardana et al. (2023)
Potato processing wastewater	Single Chamber	Graphite plate	0.19 V	6.2	94%	Cr: 58%, Pb: 62%, Cu: 55%	Toczyłowska-Mamińska and Mamiński (2023)
Banana peel slurry	Single Chamber	Carbon felt	610 mV	42	91%	Pb: 84%	Sumatkar et al. (2025)

Potato solid waste	Double Chamber	Carbon felt	480 mV	21	87%	Pb: 74%, Cu: 70%	Toczyłowska-Mamińska and Mamiński (2023)
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Consequently, this research aims to leverage the abundant cellulose content of rotten rice flour (RRF) as a substrate in MFCs to promote microorganism proliferation, stimulate bioenergy generation and heavy metal bioremediation such as aluminum ( $\text{Al}^{3+}$ ), copper ( $\text{Cu}^{2+}$ ), and lead ( $\text{Pb}^{2+}$ ) from wastewater. RRF was selected for its cost-effectiveness, high availability, and relatively high cellulose content, which may enhance microbial activity (Ibrahim *et al.*, 2025).

## II. MATERIALS AND METHODS

### A. Reagents and materials

The Rotten rice flour used in this research was purchased from the International Market located in Felele, Lokoja, Kogi State. Standard solutions containing 1000 mg/L Aluminum ( $\text{Al}^{3+}$ ), copper ( $\text{Cu}^{2+}$ ) and lead ( $\text{Pb}^{2+}$ ) ions were obtained from the Central Research Laboratories, Kogi State Polytechnic, Lokoja. Graphite rods, digital multimeter and the external resistor were purchased from Chigoz Electronics in Adankolo, Lokoja, Nigeria. The graphite rods function as the anode and cathode in our single-chamber MFC arrangement while the external resistor of 1 kilohms was applied. All chemicals used were of analytical grade and sterilized properly.

### B. Source of inoculation

Domestic wastewater was collected from a nearby pond and spiked with toxic metal ions ( $\text{Al}^{3+}$ ,  $\text{Cu}^{2+}$ , and  $\text{Pb}^{2+}$ ) at a concentration of 50 ppm to create synthetic wastewater which was utilized as the inoculum for our single-chamber MFC studies. The physicochemical characteristics of both fresh and synthetic wastewaters are presented in Table 2.

Table 2 Properties of the wastewater in the current study.

Physicochemical Parameters	Waste water	Synthetic water
Colour	Dark Brownish	Dark Brownish
Odour	Irritating	Irritating
Temperature	25°C	25°C
PH	6.22	6.12
Conductivity	125 $\mu\text{S}/\text{cm}$	300 $\mu\text{S}/\text{cm}$
$\text{Al}^{3+}$	0 ppm	50 ppm
$\text{Cu}^{2+}$	0 ppm	50 ppm
$\text{Pb}^{2+}$	0 ppm	50 ppm

### C. Rotten Rice Flour Preparation

This work used rotten rice flour (RRF) as a naturally occurring, organic substrate. To assess the possibility of improvements in MFC performance, 5 g of the substrate was introduced to the MFC every day. The decaying rice was kept at room temperature for an entire day before being pulverised

into a fine powder to enhance microbial growth and metabolism. The powdered flour was introduced directly into the MFC, providing a rapidly attainable source of energy for the microbes (Idris *et al.*, 2025).

### D. Configuration and operation of MFC

A single-chamber MFC arrangement with dimension 22.5 cm in length and 10.5 cm in diameter with an area of 17.25  $\text{cm}^2$  with a total working volume of 500 mL was utilized in this study. The cell chamber contains 50 ppm each of pollutant metal wastewater along with the prepared rotten rice which was added daily to the cell. Graphite rods, measuring 8.0 cm in height and 1.5 cm in radius, were placed vertically as the anode and cathode electrodes, thus finalizing the MFC configuration. Aluminum wire was utilized to merge the anode and cathode electrodes with 1 k $\Omega$  resistor added to connect the MFC to an external circuit as shown in Figure 1. The MFC cycle was carried out under ambient conditions for a duration of 37 days, during which the voltage output was continuously monitored and recorded (Alshammari, Aleid, *et al.*, 2025; Fadzli *et al.*, 2021).

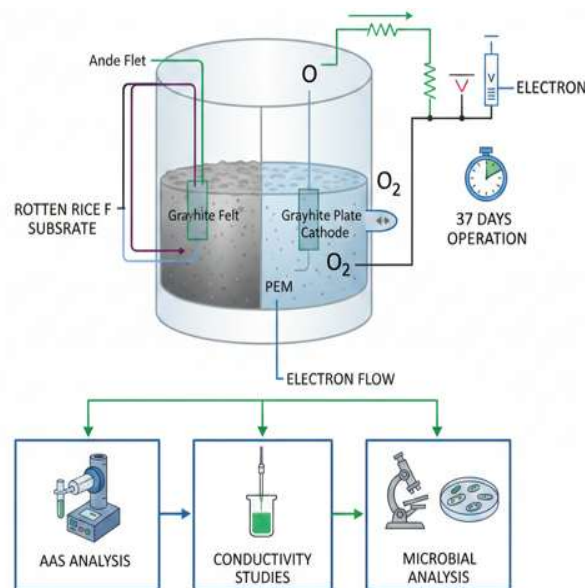


Figure 1 The prototype MFC and experimental design used in this study

### E. Electrochemical Studies

The generation of voltage was monitored and recorded every 24 hours making use of digital multimeter to observe the ionic interactions between the anode and cathode. The generated current was calculated using Ohm's Law. Current density (CD), power density (PD), and internal resistance ( $r$ ) were calculated using equations (1-3), where 'V' represents

the voltage output, 'I' denotes the current, 'A' indicates the electrode area, 'R' signifies the external resistance (Ibrahim et al., 2025)

$$V = IR \quad (1)$$

$$PD = \frac{V^2}{A \times R} \quad (2)$$

$$CD = \frac{V}{A \times R} \quad (3)$$

Where PD refers to power density ( $\text{mW}/\text{m}^2$ ), CD refers to current density ( $\text{mA}/\text{m}^2$ ), V is the output voltage (mV), A is the area of anode ( $\text{m}^2$ ) and R is the external resistance ( $\Omega$ ).

#### F Heavy Metal Bioremediation Efficiencies

Bioremediation efficiencies of the heavy metals within the MFC were evaluated using atomic absorption spectroscopy (AAS) (AAS-PerkinElmer A400; Waltham, MA, USA) outlining previous procedure. Every five days, 4 mL of operational wastewater from the MFC was collected to analyze the remaining metal concentrations. The bioremediation efficiency (BE) of the metals was calculated using Equation 4 based on the output gotten from AAS. In Equation 4,  $C_i$  refers to the initial concentration of metal ions, while  $C_f$  entails the final concentration of metal ions post-treatment. After 37 days of MFC operation, the anode electrode was carefully removed from the MFC and rinsed with deionized water to remove the remaining contaminants (Idris, Al-Zaqri, et al., 2023).

$$BE(\%) = \frac{C_i - C_f}{C_i} \times 100 \quad (4)$$

#### G. Microbiological Investigations

A sterile scalpel was used to gently scrape a section of the anode surface to get microbial samples, which were transferred to sterile distilled water in separate Falcon conical tubes. To isolate the bacteria, the sample was spread onto sterile nutrient agar plates and incubated for 24 hours at 35 °C. Bacterial colonies exhibiting distinct morphologies were selected and purified through serial sub-culturing in nutrient broth (Yaqoob, Ibrahim, & Yaakop, 2021). Biochemical tests are methods used in laboratories that identify and classify microorganisms by considering their metabolic and biochemical characteristics. These tests are intended to evaluate the presence, lack, or activity of certain enzymes involved in distinct metabolic of the anodic biofilms.

### III. RESULTS AND DISCUSSIONS

#### A. Substrate Composition used in the Study and its Metabolism

Table 3 Characteristics of the Rotten Rice Flour (RRF) used in the current study

Substrates	Moisture content (%)	Cellulose (%)	Hemicellulose (%)	Lignin (%)
RRF	10.9	42.9	23.8	22.4

#### B. Voltage generation and polarization Studies

The reaction in the MFCs lasted 37 days, utilizing 5 g of rotten rice daily as organic substrate source in the MFC. Figure 2(a) depicts the result of voltage generation with peak

The Rotten Rice Flour used as substrate in this study exhibited 42.9 % cellulose, 23.8 % hemicellulose, and 22.4 % lignin, as presented by the results in Table 3. The presence of these components in the substrates allows for microbial metabolism. During the MFC operation, the organic substrates were metabolized by electrogenic microbes, producing high amount of voltage initially which later drop as result of substrate depletion with the microbes approaching decline phase (Idris et al., 2025). Decomposed rice flour is degraded in MFC via the enzymatic hydrolysis of starches and proteins into fermentable monomers, which are then converted to organic acids through anaerobic fermentation. These acids are oxidized by anodic bacteria, which results in the release of electrons and protons. The degradation from spoilage improves the solubility of the substrate and provides an initial microbial community, thereby enhancing the availability of electrons for bioelectricity generation (Aleid et al., 2023; Pandit et al., 2021). The metabolism and mechanism of heavy metal remediation based on the study is shown in Figure 2

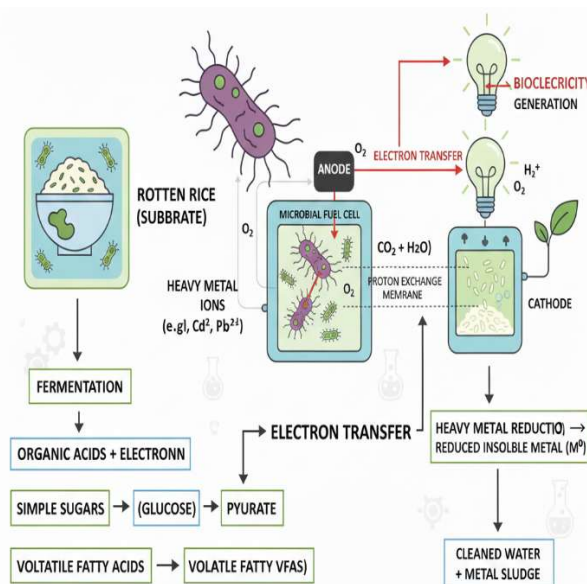


Figure 2 Metabolism and mechanism of heavy metal remediation based on the current study

voltage output of 200 mV attained on day 21. However, the voltage declines rapidly to 60 mV on day 37, marking the end of the operational time. The observed decrease in voltage output could be as a result of depletion of bacterial biomass

since the microbes may utilize the available nutrients and reached the end of their development phase. The initial voltage output was minimal, but it gradually increased until day 23, when it began to drop. Voltage generation may also decline as exoelectrogens become less able to use the constant supply of the substrate for metabolic activity, leading to a decrease in metabolism and a progressive approach to bioremediation completion. While the maximum voltage was observed on day 21, this could also mean the increase the solubility of the toxic metal as reported in the prior study (Chen *et al.*, 2017). A polarization experiment was investigated to determine how changing external resistance affects MFC performance. Resistance values ranged from  $3.5\text{k}\Omega$  to  $100\ \Omega$ . Figure 2(b) shows the outcomes of this experiment. At high external resistance values, the system had limited electron transport and voltage stability. Conversely, with low external resistance values, rapid

electron transport reduced voltage stability due to the rise in the current flow.

### C. Conductivity Studies (CS)

To assess the electrolyte conductivity throughout MFC operation, the conductivity of the cell was monitored at various time intervals over the period of 37 days. Figure 3 shows that the conductivity value on the first day was  $300\ \mu\text{S}/\text{cm}$  and subsequently increased until the 10th day ( $750\ \mu\text{S}/\text{cm}$ ), demonstrating increasing ionic strength. After day 10, the conductivity rapidly increases reaching a value of  $1000\ \mu\text{S}/\text{cm}$  on day 25 and decreases to  $500\ \mu\text{S}/\text{cm}$  on the final day of the MFC operation. It can be observed that the conductivity values were in agreement with the output voltage obtained during the study period. The peak conductivity observed on the 25th day may occur as a result of rapid electroactivities during that period.

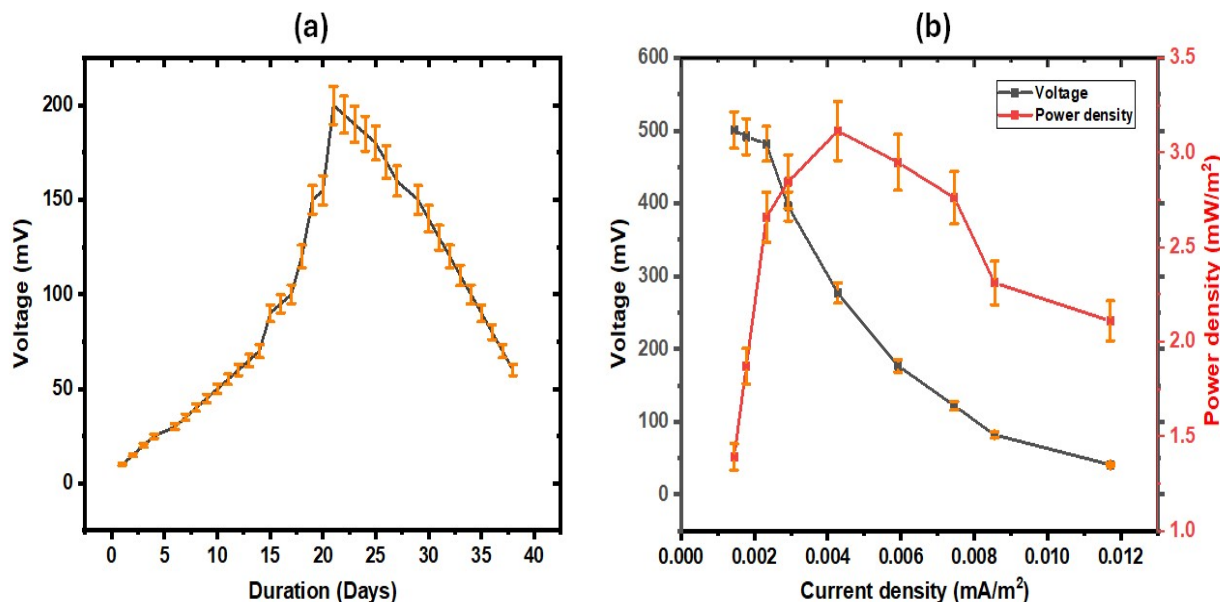


Figure 3 (a) Daily Voltage Output in the MFC for 37 days (b) Polarization Curve

However, the subsequent decline in conductivity could be a result of factors such as redox potential, pH, organic substrate availability, temperature, and microbial stability may function in reducing the MFC's efficacy. For this study, the achieved current density was approximately  $0.012\ \text{mA}/\text{m}^2$ , resulting in a power density of  $3.34\ \text{mW}/\text{m}^2$ . The rotten rice substrate initially enhances voltage but fails to maintain a high electron flow, leading to a low current density. Although biofilm development may enhance voltage stability but will not necessarily lead to increased current as the substrate becomes depleted. Power density is significantly affected by the resistance of the system. During later stages of the cycle, if resistance decreases, power density might temporarily rise despite a low current density (Rojas-Flores *et al.*, 2021).

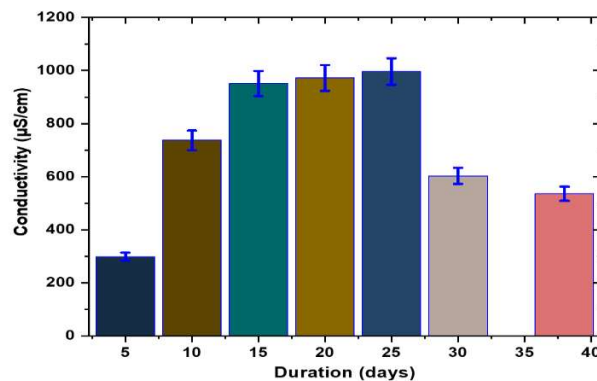


Figure 4 Conductivity studies for the period of 37 days  
D. Bioremediation Efficiency of the Heavy Metal



Bioremediation of toxic metals in MFCs is a crucial operating parameter studied during the recent time due to the dual ability to generate bioenergy and reduce contaminants. In the current study, the rotten rice flour was used for achieving these objectives. Toxic metal remediation results observed during the experiment is illustrated in Table 4. The optimal concentration of 50 ppm has been found to be effective in heavy metal remediation in MFC systems in previous studies, such as the one reported by (Li et al., 2018). Their study determined the concentrations of  $Pb^{2+}$  and  $Cr^{6-}$  found that 50 ppm not only gave the largest percentage of metal removal

and also not affect the toxic out-turn on the bacteria population. The final bioremediation efficiencies were determined to be 83.78, 85.44%, 87.10% for  $Al^{3+}$ , 85.54 %, 87.54, 88.90 for  $Cu^{2+}$  and 87.00%, 90.92%, 90.34% for  $Pb^{2+}$  respectively, showing that the MFC system was active in ameliorating toxic metal levels. The study also indicated a progressive decline in the concentration of the metal ions within the course of the 37-day operation. The bioremediation efficiency increased progressively over time, exceeding 70% for all metals by day 20.

Table 4 Trends in Bioremediation Efficiency of the Contaminants

Organic Substrate	Metal Contaminants	Initial Concentration	Operational Days	Final Concentration	Bioremediation efficiency (%)
Rotten Rice Flour	$Al^{3+}$	50 ppm	0	0.00	0.00
			5	35.00	30.00
			10	29.40	41.20
			20	15.50	69.00
			30	8.11	83.78
			35	7.28	85.44
			37	6.45	87.10
	$Cu^{2+}$	50 ppm	0	0.00	0.00
			5	29.30	41.40
			10	27.95	44.10
			20	14.30	71.40
			30	7.24	85.54
			35	6.23	87.54
			37	5.55	88.90
	$Pb^{2+}$	50 ppm	0	0.00	0.00
			5	28.45	43.10
			10	23.25	53.50
			20	12.24	75.52
			30	6.50	87.00
			35	4.54	90.92
			37	3.33	93.34

#### E. Identification of Bacteria on the anode

In other to identify the microbes deposited at the anode, morphological and biochemical tests were carried out. Biochemical tests carried out includes Gram staining, oxidase, catalase, citrate, indole and motility test. The isolates were identified based on their reaction to several substrates utilized in biochemical characterization. Among the four isolates, BAI and BA4 were Gram-negative while BA2 and BA3 were Gram positive described in Table 5. Gram-positive bacteria are characterized by having a simpler structure which comprises 90% peptidoglycan and 10% teichoic acid. Several Gram-positive bacteria may have increase negative surface charge as a result of covalent bond between

peptidoglycan and teichoic acid (Caudill et al., 2020). For the motility test carried out on the isolate, 50% nutrient agar

was used. This medium has a very soft architecture ensuring easy mobility of bacteria leading to cloudiness. BAI isolate was motile while BA2, BA3 and BA4 was non-motile. A widespread growth zone that extends from the line of inoculation provides evidence of bacterial motility (Aryal, 2021). BA1 was identified as *Escherichia coli* while BA2, BA3 and BA4 are *Staphylococcus* sp., *Bacillus* sp., and *Serratia* sp. Respectively. *E. coli* is a metal-tolerant microorganism that can conduct limited extracellular electron transfer using natural mediators such as flavins, although its

efficiency is lower compared to traditional exoelectrogens (Jayatilake et al., 2024). The biochemical pathways of cellulose degradation and electron transfer in MFCs specifically involving *E. coli*, *Bacillus*, *Staphylococcus sp.*, and *Serratia sp.* can be illustrated in Figure 5.

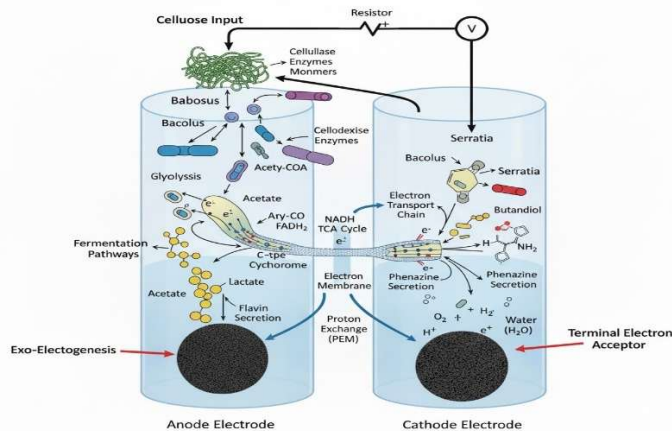


Figure 5 Proposed biochemical pathways of cellulose degradation and electron transfer mechanism based on this study.

*Staphylococcus* species exhibit weak electron transfer capabilities and are more effective within biofilms. Certain species generate redox-active substances that facilitate electron shuttling, but their performance is variable and generally inferior to that of exo-electrogens found in soil and wastewater (Naaz et al., 2023). *Bacillus* species typically form biofilms and can produce electron-shuttling compounds which includes phenazines and quinones in some strains displaying moderate exo-electrogenic behavior and performing better when attached to anode surfaces (Saraf et al., 2025). Some *Serratia* sp strains synthesize prodigiosin, a redox-active pigment that can serve as an electron mediator, which improves their exo-electrogenic efficiency compared to *E. coli* or *Staphylococcus*; however, they still fall short of the performance exhibited by key electroactive bacteria like *Geobacter* or *Shewanella* (Cheng et al., 2023; Santos et al., 2022).

Table 5: Morphological and Biochemical tests of the isolate

[illegible]

BA4	Rod shaped characteriz ed by red pigment, circular and smooth colonies	Gram -													<i>Serratia</i> sp
		ve Rods	+	+		-	+	-		-	+	+		-	

IV. CHALLENGES AND FUTURE PROSPECTS

MFC technology is growing in its popularity due to its application in various field of science(Fadzli et al., 2021). Despite its unique nature, MFC frequently encounter challenges as a result of compatibility of the nature of electrodes meeting up with the mobility of electrons and the efficiency of organic substrate in increasing microbial activities (Ibrahim et al., 2025). Some current limitations, challenges and possible solution regarding MFC progress have been highlighted in Figure 6. In the current study, a considerable number of voltages were generated with the limitation of operating the MFC system for 37 days leading to decline in the power generation. MFC operation on a larger scale will require a stable organic substrate over time. For purposes of scaling up MFC to industrial scale, the long-lasting operational organic substrate must have high stability and optimal amount of glucose production. Another critical factor to consider in MFC design is the electrode material. Anode material is very essential component that influences

MFCs performance. Anode properties such as biocompatibility, conductivity, large surface area and durability are very important factors (Yu et al., 2021). The MFC had difficulties to produce enough energy owing to the material used as electrodes. Although graphite is capable of conducting electricity, it possesses a greater internal resistance compared to porous or woven carbon structures, which results in voltage drops before the electrons reach the circuit. Additionally, it lacks surface functional groups that would enhance direct extracellular electron transfer, leading microorganisms to heavily depend on soluble mediators that may not be sufficient or stable. In its unmodified state, graphite exhibits lower hydrophilicity, which diminishes the attachment efficiency of electroactive bacteria like *Escherichia coli* when applied in microbial fuel cells (MFCs) or mixed inoculum experiments. Furthermore, there are no metal oxide coatings or conductive polymers present to enhance redox reactions on the surface of the electrode(Guerrero-Barajas et al., 2022; Yuan et al., 2025).

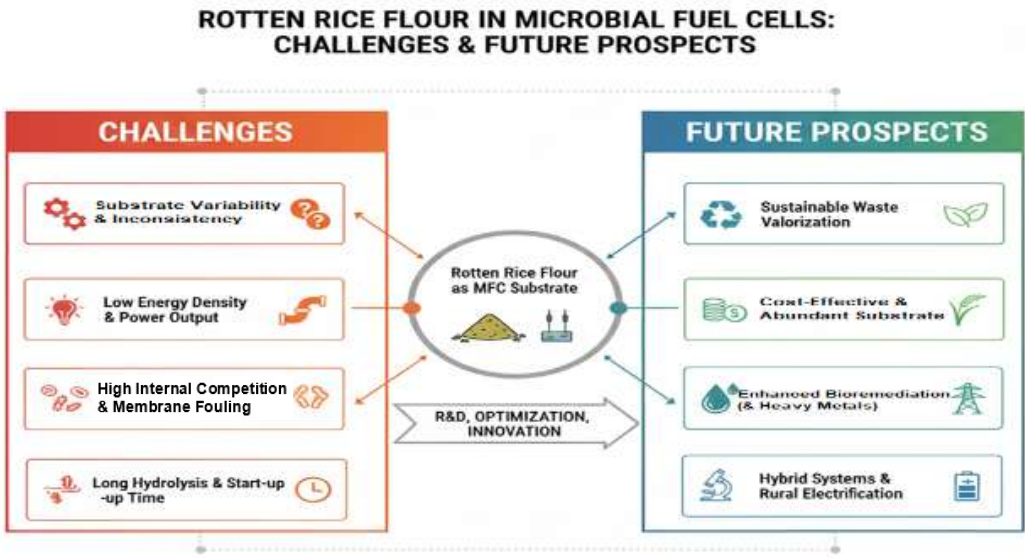


Figure 6 Challenges and future prospects for this study



## V. CONCLUSION

This study investigated the suitability of rotten rice flour to be used as an organic substrate in an MFC for bioremediation of toxic metals in synthetic wastewater treated with the toxic metals while generating bioenergy. The study yields a good result, with remediation efficiency of more than 90% at the end of the operation and a voltage output of 200 mV attained at the 21-day of MFC operation. The rotten rice flour utilized as organic substrate exhibited considerable number of voltages making it a suitable for the MFC. Microbiological activities on the anode surface contributed a vital role in metal biodegradation process. Rotten rice flour serves as a scalable substrate for MFC due to its significant organic load from starch, minimal need for pre-sterilization, and broad availability as an agricultural by-product. However, when scaled up, its particulate form can lead to limitations in mass transfer, risks of pore clogging, and competing anaerobic processes that can divert electrons away from electricity production. Thus, successful scalability relies on adequate pre-hydrolysis, continuous mixing, stabilization of conductivity, and the use of high-surface-area conductive anode materials.

## AUTHOR CONTRIBUTIONS

**A.I. Suleiman:** Conceptualization, Methodology, software, validation, writing – original draft, Writing – review & editing. **M. O. Idris:** Supervision, writing – original draft, Writing – review & editing. **E.T. Omejeh:** Writing – review & editing. **A.I. Ahmad:** Writing – review & editing. **C.B. Okpanachi:** Writing – review & editing. **M.A. Yayo:** Writing – review & editing. **W.E. Edegbe:** Writing – review & editing. **H. A. Audu,** Writing – review & editing. **D. Shehu** Writing – review & editing

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